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(71) Applicant(s)
Optoplan AS

(Incorporated in Norway)

Björkhaugveien 27, N-7002 Trondheim, Norway

(72) Inventor(s)
Jon Thomas Kringlebotn

(74) Agent and/or Address for Service
Brian R Lucas
Lucas & Co, 135 Westhall Road, WARLINGHAM,
Surrey, CR6 9HJ, United Kingdom

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WO 95/31020 A **US 5166940 A**

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(54) **DFB fibre lasers**

(57) A DFB fibre laser 4 doped with one or more rare-earths is provided with distributed feedback via a fibre Bragg-grating, which gives rise to only two orthogonally polarised wavelengths. The separation between the wavelengths may be tuned by changing the birefringence of the fibre, the beat frequency being detected by a polarizer 5, photodetector 6 and frequency analyzer 7. The laser may be applied as a polarimetric sensor in which an asymmetrical force changes the wavelength separation, or as a tunable two-wavelength source. A particular preferred field of application is for measuring the pressure in pipes, to determine the flow.
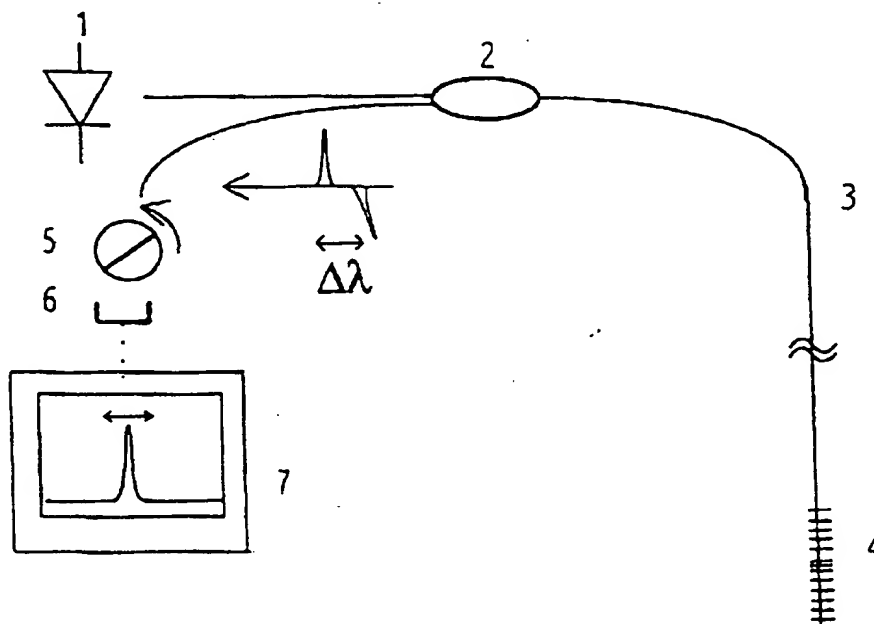
Fig.2a

At least one drawing riginally filed was informal and the print repr duced here is taken from a later filed formal copy.

This print takes account of replacement documents submitted after the date of filing to enable the application to comply with the formal requir ments f the Patents Rules 1995
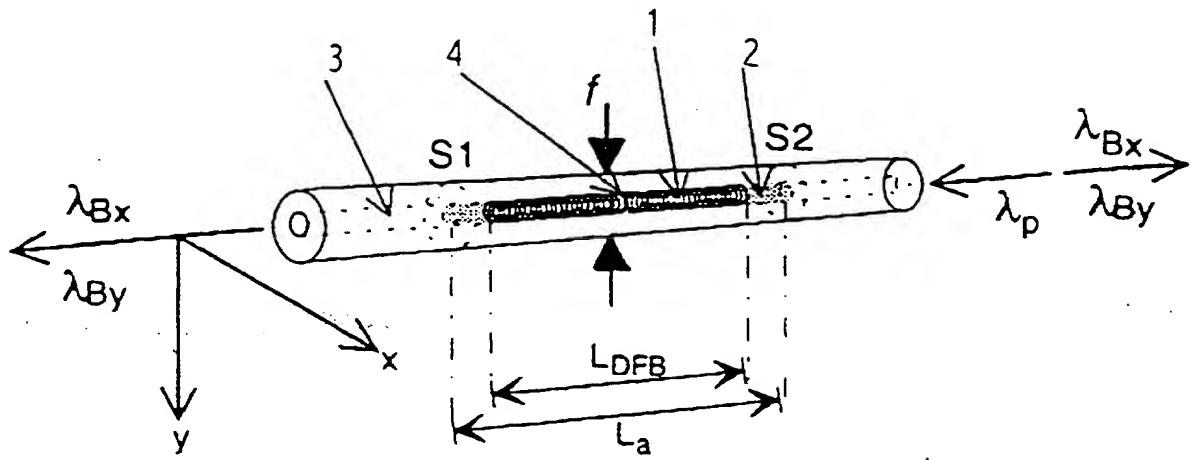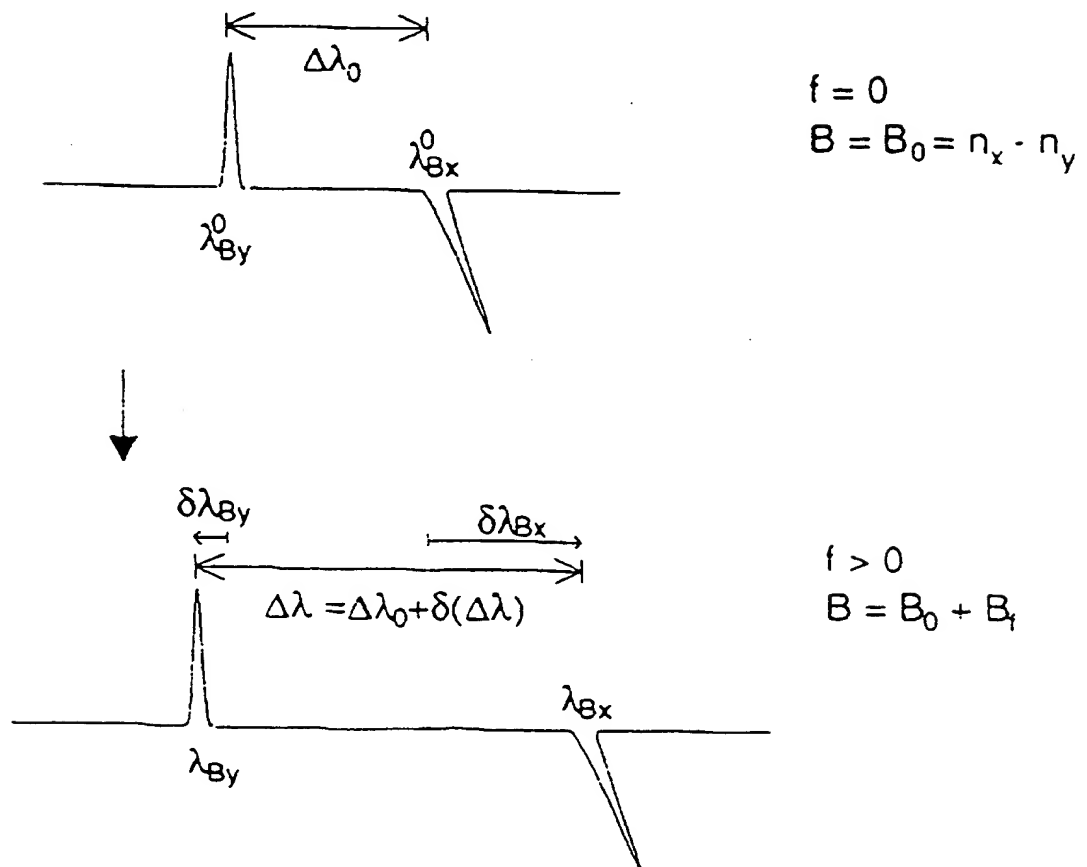
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Fig.1a

$$f = 0$$
$$B = B_0 = n_x - n_y$$

$$f > 0$$
$$B = B_0 + B_f$$

Fig.1b

Fig.2a

$$\Delta \nu = \frac{c}{\lambda^2} \Delta \lambda$$

$\Delta \nu_0$

$\Delta \nu_{Beat} \leq 2\Delta \nu_0$
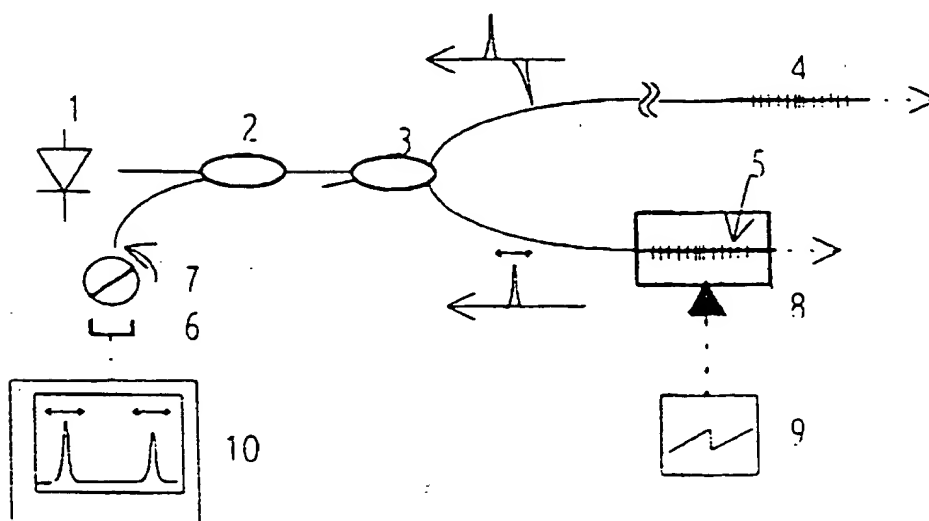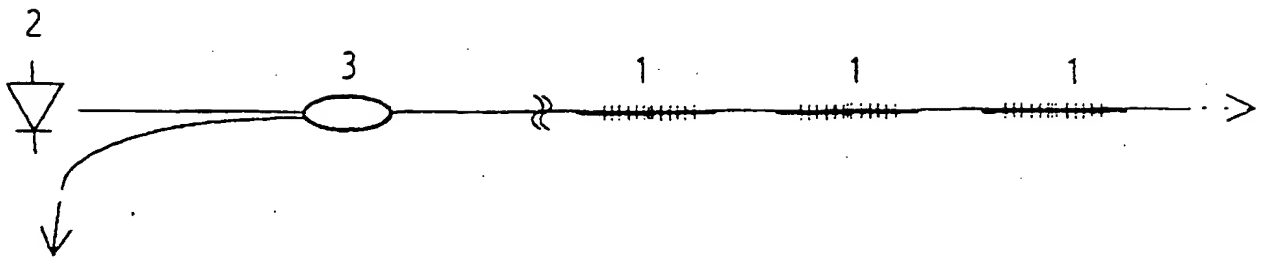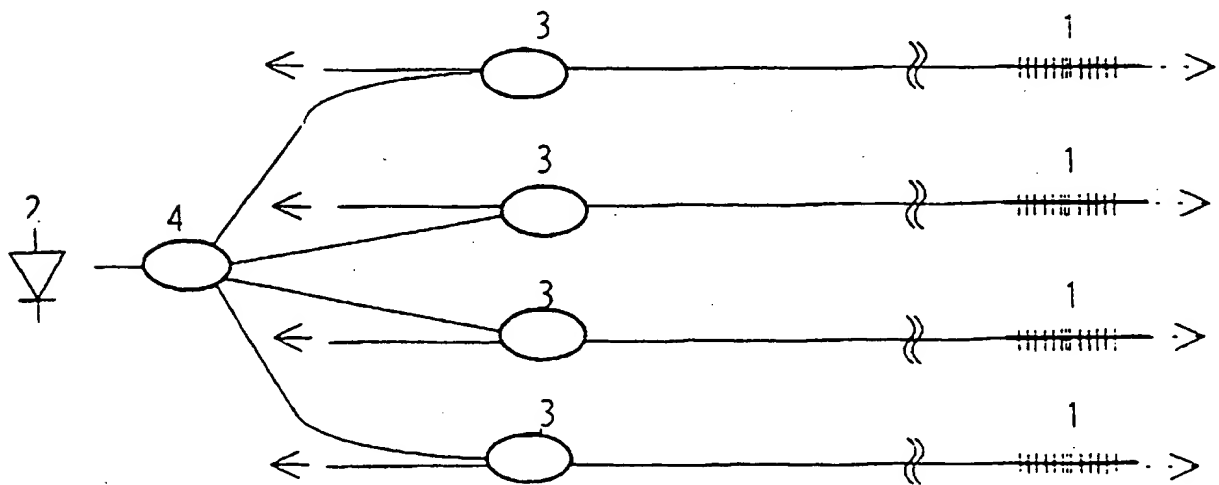
$\Delta \nu$
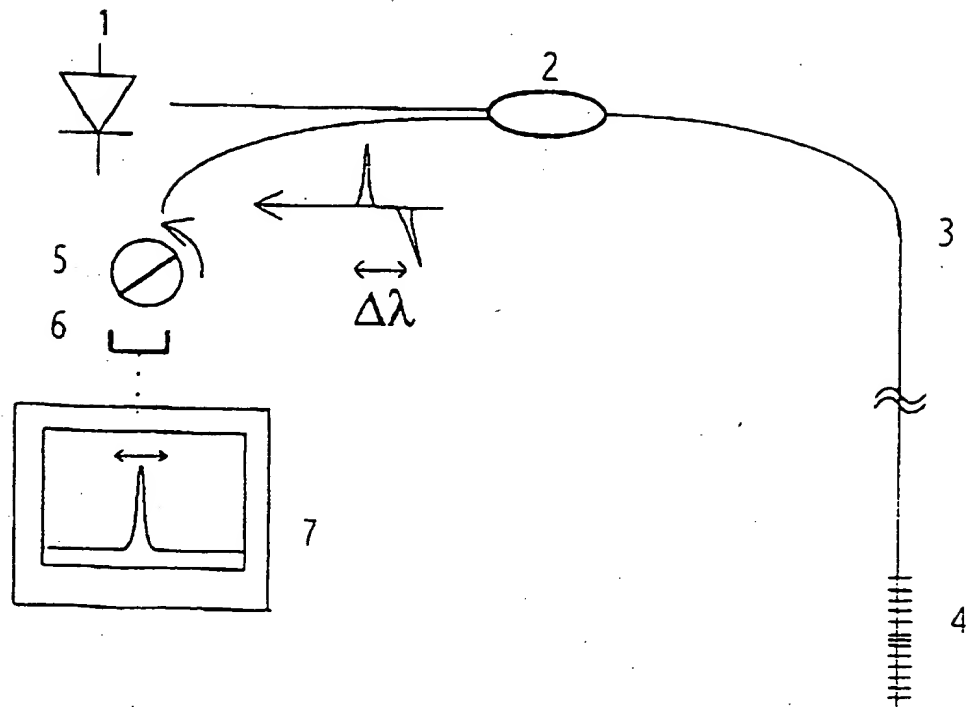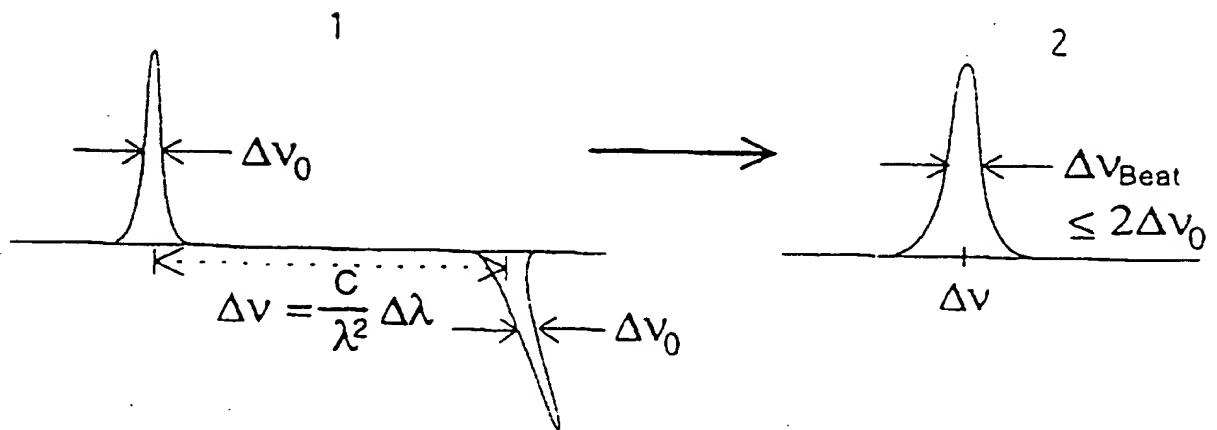
Fig.2b
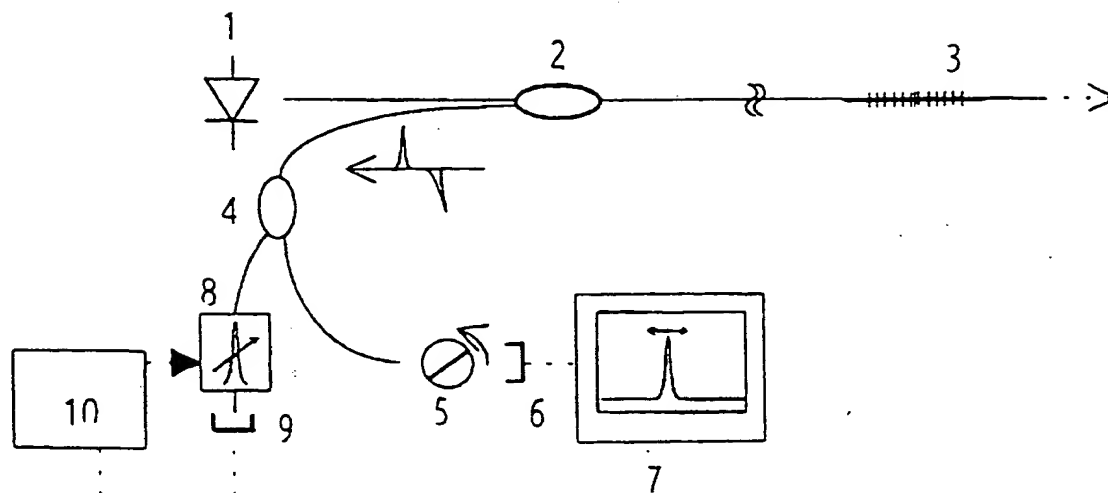
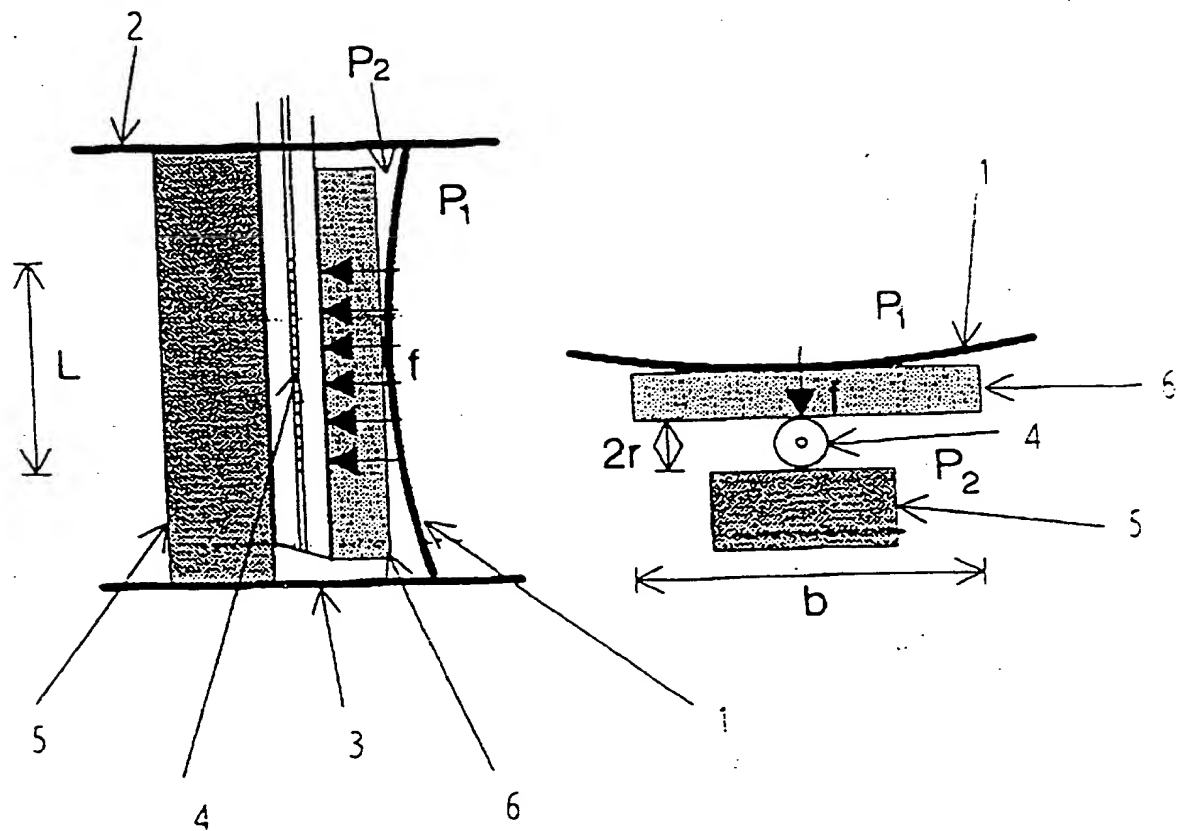**Fig.3a**

Fig.3b

Fig.4a

Fig.4b

Fig.5

Background

This invention relates to an optical end-pumped
fibre laser, doped with one or more rare earth ions and
with distributed feedback provided by one single fibre
Bragg grating, which oscillates at two orthogonally
polarised wavelengths.

A patent application for a rare-earth doped fibre
laser with distributed feedback (fibre DFB laser) was
recently filed [UK Patent Application No. 9409033.9,
filed 6 May 1994, and PCT/GB95/01026], and experimental
results are later published [J.T. Kringlebotn, J.-L.
Archambault, L. Reekie, D.N. Payne, "$Er^{3+}:Yb^{3+}$-codoped
fibre distributed-feedback laser," Optics Letters, Vol.
19, pp. 2101-2103, 1994]. When end-pumped by an optical
source (typically a semiconductor laser) such a fibre
DFB laser will, with an optical phase-shift of π in the
fibre Bragg grating, oscillate at two orthogonally
polarised wavelengths only (see Kringlebotn et. al.
1994). These two (Bragg) wavelengths are given by:

$$\lambda_{Bx}=2n_x\Lambda \qquad\qquad (1a)$$

and

$$\lambda_{By}=2n_y\Lambda \qquad\qquad (1b)$$

where n_x and n_y are the effective refractive indices of
the two orthogonal polarisation eigenstates x and y of
the fibre laser, and L is the physical period (pitch) of
the fibre Bragg grating. The wavelength separation $\Delta\lambda$ =
λ_{Bx} - λ_{By}, is given by:

$$\Delta\lambda + 2B\Lambda \qquad\qquad (2)$$

where the birefringence B of the fibre is defined as B =

$n_x - n_y.$

A change in the birefringence B and/or the grating pitch, i.e. the fibre length, results in a change in $\Delta\lambda$, d($\Delta\lambda$), such that

$$\frac{\delta(\Delta\lambda)}{\Delta\lambda} = \frac{\delta B}{B} + \varepsilon \qquad (3)$$

where $\varepsilon = \delta\Lambda/\Lambda = \delta L/L$ is the fibre strain. L is the length of the fibre laser. It is known that the birefringence of an optical fibre can be changed by squeezing, bending or twisting the fibre.

Several fibre optic sensors based on so-called DBR (distributed Bragg-reflector) fibre lasers with two fibre Bragg grating end-reflectors, or one grating and one broadband mirror, have been demonstrated [A.D. Kersey, K.P. Koo, and M.A. Davis, "Fiber optic Bragg grating laser sensors," Proceedings SPIE, Vol. 2292, 1994]. This was done either by using the lasers for wavelength interrogation of passive fibre Bragg grating sensors, or by employing the lasers as the sensor elements themselves. In all these sensors one measures the Bragg wavelength of one or more fibre grating sensors, and the sensors have the advantage (over passive grating sensors interrogated by broadband sources) that all optical power is concentrated within the grating bandwidth (with a signal bandwidth potentially much narrower than the grating bandwidth), such that the sensor system can provide high, optically limited, signal-to-noise ratios. By employing the fibre laser itself as the sensor element (remotely pumped by a semiconductor laser), the emitted laser wavelength will be proportional to the measurand, and the need for a tuneable interrogation laser is eliminated. This enables an very high resolution, a fast response, and enables wavelength

multiplexing of many sensors. Such a fibre Bragg grating laser sensor can either be operated multi moded (laser length L >> 5cm), where the optical signal bandwidth is limited by the grating bandwidth (10-100GHz), or single
5   moded (L < 5cm), where the linewidth is typically 1-500kHz. This implies that single mode operation provides the highest resolution.

In all these sensors the wavelength(s) of one or more fibre Bragg gratings are measured, which requires a
10   system for accurate readout of the wavelength(s). This can often be difficult to realise (for a required accuracy). A different, simple and elegant approach, based on a dual wavelength DBR fibre laser with two fibre Bragg grating end-reflectors, was recently demonstrated [G.A.
15   Ball, G. Meltz, and W.W. Morey, "Polarimetric heterodyning Bragg-grating fiber-laser sensor", Optics Letters, Vol. 18, pp. 1976-1978, 1993]. In this laser sensor the separation between the two fibre Bragg gratings was made small (<5cm), such that the number of oscillating long-
20   itudinal modes were reduced to two orthogonally polarised wavelengths (which belonged to neighbouring longitudinal orders).

In this dual-mode DBR fibre laser sensor the wavelength separation is measured, which in addition to the
25   laser length and fibre birefringence, depends on the relative phase of the two wavelengths upon reflection for the two grating end-reflectors, and also on the longitudinal order of each of the polarisation modes. By sending the laser light through a polariser the two
30   wavelengths can mix in a detector and generate an electrical beat signal with frequency equal to the optical frequency separation between the two wavelengths (typically 0.5-50GHz). Hence, a very simple, accurate and fast electronic readout of the separation, and hence the
35   measurand which affects the fibre laser, is obtained.

The optical linewidth of each of the two modes in the DBR laser demonstrated by Ball et.al. was very narrow (a factor 10^{-7}-10^{-3}) compared to the wavelength separation. Hence a sensor based on such a laser will have a very high resolution and a wide dynamic range.

The DBR fibre laser reported by Ball et. al. was used as a strain sensor, i.e. the wavelength separation was changed by applying a strain to the fibre laser (the two gratings and the doped fibre in-between), but it was mentioned that all perturbations which change the cavity length or the birefringence will give rise to a change in wavelength separation, and hence beat frequency.

The problem with this dual polarisation mode DBR fibre laser sensor (and single mode DBR fibre laser based on measuring the wavelength) is that it consists of two separate fibre gratings and a fibre section in-between, which need to be exposed equally to and have the same response to the measurand to obtain a correct measurement and avoid mode hopping (uncontrolled shifts of longitudinal mode) or ceasing of laser action. The two gratings should also have the same Bragg wavelength and birefringence.

A central problem of all fibre optic sensors, including sensors based on fibre Bragg gratings, is to separation between two measurands, for instance pressure and temperature, or strain and temperature. Fibre Bragg grating sensors are, as mentioned above, normally based on measuring induced shifts in Bragg wavelength. Since both (for instance) pressure, strain and temperature variations induce shifts in Bragg wavelength will not a measurement of the reflected Bragg wavelength from a sensor grating separate between to different measurands. A series of methods have been proposed to solve this problem, for instance by using two gratings with different response to one (or both) of the measurands, or by

employing two overlapping gratings with different Bragg wavelengths, and hence different response, but so far this problem has not been satisfactory solved with only one fibre Bragg grating.

5   In various interferometric fibre optic sensors it is desirable to use two sources with different wavelength and tuneable wavelength separation, or ideally one source with two wavelengths and tuneable wavelength separation, (for instance) to ensure so-

10   called quadrature operation at all times, or alternatively to increase the linear (unambiguous) measuring range. It is also known that two stable wavelengths can be employed for generation of a beat signal which through non-linear propagation in a dispersion profiled

15   fibre will develop into a pulse train with tuneable (and stable) pulse repetition frequency equal to the optical frequency separation between the two wavelengths. This is demonstrated with two coupled fibre lasers, with four fibre Bragg gratings and two different wavelengths, in

20   series along the same fibre [S.V. Chernikov, J.R. Taylor, and R. Kashyap, "Integrated all optical fibre source of multigigahertz soliton pulse train", Electronics Letters, Vol. 29, pp. 1788-1789, 1993].

25   **Objects**

The main object of the invention is to provide an end-pumped fibre laser which can be employed as sensor for measurement of a measurand, for instance pressure, independently of other parameters, for instance tempera-

30   ture, or for measurement of two independent measurands, for instance pressure and temperature.

In particular it is the object to provide a fibre optic sensor based on a fibre Bragg grating which can measure pressure, for instance in cells for flow mea-

35   surements, without being affected by changes in tempera-

ture.

Another object is to obtain a means for using an end-pumped fibre laser, as mentioned above, as a source with two orthogonal wavelengths with tuneable separation between the two orthogonal wavelengths.

Addition objects for the invention will become clear from the following part of the description.

Invention

The invention is described in Claim 1, with Claim 2-8 stating especially advantageous characteristics.

By means which primarily changes the fibre birefringence B a DFB fibre laser with tuneable/adjustable separation between the two orthogonal wavelengths can be constructed. The invention is particularly interesting as a sensor, where the measurand (external perturbation) induces a birefringence in the fibre, for instance through an asymmetric, transverse force on the fibre, such that the measurand, for instance pressure (or differential pressure) can be determined by measuring the wavelength separation. In a preferred embodiment this is done by mixing the two wavelengths in a photo detector resulting in a measurable electrical beat frequency. Notice that any measurands which introduces a change in fibre birefringence (or effective refractive index), or a change in fibre laser length, can be measured by the proposed fibre laser sensor.

When a measurand induces a birefringence in the fibre laser, another measurand, which does not (or to a small extent) induces such a birefringence, for instance temperature or strain, can be measured, since in such a case the wavelength separation, which is proportional to the birefringence, and the two orthogonal wavelengths, which are proportional to the refractive indices along the two orthogonal eigenaxises, will have different

dependence on the two measurands. Hence, by measuring both the wavelength separation and one of the wavelength (or by measuring both wavelength) both the two independent measurands can be determined.

5   The wavelength separation will also depend on the laser cavity length, which is affected by for instance temperature and strain. The sensor can, however, be constructed such that changes in wavelength separation owing to changes in for instance temperature and strain

10   becomes small compared to chances which are caused by changes in the measurand inducing the birefringence, and which one primarily are interested in measuring. Hence, the invention employed as a sensor can to a great extent separate between two different measurands, for instance

15   pressure and temperature, and hence in many cases make temperature compensation in pressure measurements (which for many other sensors are necessary) unnecessary.

The invention also concerns a DFB fibre laser source with tuneable separation between the two orthogo-

20   nal wavelengths. Such a source can for instance be employed as a dual-wavelength source for interferometric fibre optic sensors, where two wavelengths with correct separation can ensure quadrature operation or alternatively increase the linear (unambiguous) dynamic range.

25   In particular will such a source be applicable in polarimetric interferometric sensors, since the two wavelengths have orthogonal polarisation states. The laser can also be employed as a depolarised source. The tuneable dual-wavelength DFB fibre laser can also be used

30   for generating a beat signal which through non-linear propagation in a dispersion profiled fibre develops into a pulse train with tuneable (and potentially very stable) pulse repetition frequency equal to the frequency separation between the polarisation modes. The

35   proposed dual-wavelength source has the advantage of

requiring only one single fibre Bragg grating.

Example

The invention is described with reference to the illustrations, in which

Fig. 1a shows a section of a DFB laser on which a transversal force is applied,

Fig. 1b shows the effect of this force on the optical spectrum of the laser,

Fig. 2a shows schematical a sensor system with a method for reading the wavelength separation $\Delta\lambda$,

Fig. 2b shows the connection between optical spectrum and electrical beat-spectrum,

Fig. 3a shows schematically a method of reading both the wavelength separation $\Lambda\lambda$ and the absolute value of one of the Bragg-wavelengths,

Fig. 3b shows schematically a method for reading both Bragg-wavelengths,

Fig. 4a and 4B shows schematically how several DFB-lasers may be arranged in series respectively in parallel, to achieve multiplexing,

Fig. 5 shows schematically a method for measuring the differential pressure by the tuneable double wavelength laser.

Fig. 1a shows a fiber DFB laser with the length L_{DFB}, which is the length of the fiber Bragg-grating 1 engraved into the core of the active fibre with a length La, which is a single mode optical fibre doped with one or more rare earths 2. This fibre is in the preferred embodiment welded to a single mode optical communication fibre 3 with connections S1 and S2. The fibre Bragg-grating contains at least one phase change 4 to achieve interference on only one wavelength (single frequency operation) in each of the orthogonal polarization states of the fibre laser, which at a preferred optical phase

change of 90° is equal to the Bragg wavelength of the fibre grating (center wavelength). At optical end-pumping of the DFB fibre laser with a wavelength λ_p the laser effect may be obtained at the two wavelengths λ_{Bx}

5 and λ_{Bx}, provided by the equation 1a) and 1b). It should be noted that the laser is emitting in both directions, enabling the use as sensor, for reflection and transmission as well.

The wavelength separation is proportional to the

10 birefringence B ($n_x - n_y$ ($n_x < n_y$), wherein n_x and n_y are the effective refractive indices of the fibre laser along the so called rapid and slow polarization axis, respectively x and y axis in Fig. 1a. The wavelength separation can be tuned be changing the birefringence

15 (or the length of the fibre), see equation 3). By pressuring the fibre in the y-direction with a force per unit of length, f, a positive birefringence Bf is induced, which for a uniform fibre equals:

20 $$B_f = \frac{4Cf}{\pi r} \qquad (4)$$

in which r is the fibre radius and C is the optical coefficient of stretch. The force should be enacted

25 along one of the polarization axes of the fibre laser (y-axis in Fig. 1a).

The change of the optical spectrum due to a force per unit of length, f, on the DFB fibre laser is shown in Fig. 1b. The birefringence is changed from B_0 till B_0

30 + B_f, which results in the change of λ°_{By} with $\delta\lambda_{By}$, while λ°_{By} is changed $+\delta\lambda_{Bx}$, to change $\Delta\lambda_0$ with $\delta(\Delta\lambda)$. It may be shown that $|\delta\lambda_{Bx}| = (5.5 \ |\delta\lambda_B|$.

Fig. 2a shows schematically the sensor system with a method for reading the wavelength separation $\Delta\lambda$.

35 Pumped light from a diode laser 1 is transmitted through

a wavelength multiplexer 2 via a transmission fibre 3, which may have a length of several kilometres, to the DFB fibre laser sensor 4, in which the received pump power provide an emmittance of light (in both direc-

5   tions) on the wavelengths λ_{Bx} and λ_{By} with separation $\Delta\lambda$. The reflected laser light is sent through the wavelength multiplexer 2 through a linear polarisator 5 to mix said two wavelengths in a detector 6 and generate an electrical beat signal with a frequency equal to the optical

10   frequency separation of the wavelengths. The polarisator should be able to change the orientation, e.g. by changing between two orientations with difference 45° to provide the beat signal at any time. The beat frequency is measured with an electrical frequency analyzer or

15   frequency counter 7.

Fig. 2b shows the connection between an optical spectrum 1) and an electrical beat spectrum 2). The orthogonal modes each have an optical line width Δv_o, while the frequency distance between the modes, Δv, is

20   equal to $c\Delta\lambda/\lambda^2$, in which c is the velocity of light in vacuum and λ is the average laser wavelength. The electrical beat spectrum has a center frequency equal to Δv and a bandwidth Δv_{beat} which is less than or equal to $2\Delta v_o$.

25   Fig. 3a shows schematically a method for reading both the wavelength separation $\Delta\lambda$ and the absolute value of one for the Bragg wavelengths. In Fig. 3a pumped light is also sent from a diode laser 1 through a wavelengths multiplexer 2 to a sensor 3. The reflected laser

30   light is split by a 1x2 coupler 4, in which a part is used to measure $\Delta\lambda$ by sending laser light through a linear polarizer 5, mixing said two wavelengths in a detector 6 and generating an electrical beat signal with a frequency equal to the optical frequency separation

35   between the wavelengths, which is measured by an elec-

trical frequency analyzer 7. The second part of the
laser light is transmitted trough a tunable, polariza-
tion independent optical transmission filter 8, into a
detector 9. The filter is scanned i wavelength or locked
5   to one of the laser wavelengths λ_{BX} or λ_{BY} by a feed back
loop 10.

     Fig. 3 b shows an alternative heterdoyne demodula-
tion technic, by which the light from the pumped laser 1
is transferred through a wavelength multiplexer 2 and is
10   split by a 1x2 coupler 3 for additionally pumping the
sensor laser 4 and also to pump a reference laser 5,
which is provided to operate in one wavelength. The
light from the reference laser 5 is mixed with the light
from the sensor laser 4 in a detector, also with a
15   polarizer 7 and by adjusting the reference laser contin-
uously over a wavelength range covering the dynamic
range of the sensor laser wavelength. The reference
laser can be tuned e.g. by stretching the grating with a
pizoelectrical fibre stretcher 8 operated by a ramp
20   signal from a signal generator 9. The beat frequency
provided between the reference laser wavelength and the
two wavelengths λ_{BX} and λ_{BY} of the sensorlaser is mea-
sured with a frequency analyzer 10 and by knowing the
wavelength of the reference laser as a function of the
25   fibre stretch, λ_{BX} and λ_{BY} may be determined with great
accuracy due to the narrow line width of the fibre
lasers. A DFB fibre laser sensor in which only one of
the two polarization modes is lasing, may be designed. A
laser of this kind may also be used as sensor, by mea-
30   suring one of the emitted wavelengths as a measure for
e.g. the fibre stretch.

     More DFB fibre laser sensors 1 (or sources) can be
multiplexed in series along one fibre, as shown in Fig.
4a, or parallel in different fibres as shown in Fig. 4b.
35   In both cases, the lasers can be pump with only one pump

source 2, wherein the pump light is introduced into the fibre lasers via wavelength multiplexers 3. In Fig. 4b the pump light is split between the different lasers by a 1xN fibre coupler 4, in which N is the number of

5 parallel fibres. The configuration of Figs. 4a and 4b can be combined. With DFB fibre lasers in series (Fig. 4a) it is important that the wavelength of the different lasers never overlap. The laser light may be uncoupled in both directions.

10 A lateral force along one of the polarization axes of the fibre will induce a birefringence. Fig. 5 shows schematically a method in which the tunable two wavelength laser is used for measurement of differential pressure $\Delta P = P_1 - P_2$. This is of importance, e.g. for

15 flow measurements. P_1 and P_1 are hydrostatic pressures on different sides of a membrane 1 which is suspended between two walls 2 and 3. The fibre laser 4 with length L i arranged on one side of the membrane 1, and pinched between the membrane 1 and a fixed bar/disk 5 which is

20 attached to the walls 2 and 3. This introduce a transversal force on the fiberlaser 4 which ideally is proportional to ΔP. To achieve a uniform force per unit of length f along the total fibrelaser, a movable disk 6 with a length >L and width b is arranged between the

25 membrane 1 and the fibrelaser 4. Alternatively the disk 6 is attached to the membrane 1. It may be assumed that $f=kb\Delta P$, in which k is a pressure-to-force transfer constant. The membrane 1 is assumed to have a stress in its non-activated condition ($\Delta P=0$) which provides bire-

30 fringence B_0 in the fibre laser, and that the differential pressure provides birefringence B_f with the same axes as B_0, wherein B_f is given by the equation 4).

The sensitivity of the sensor, S, is defined as shift in the beat frequency $\delta(\Delta v)$ per change in the

35 differential pressure, $\delta(\Delta P)$, and may be expressed as:

$$S= \frac{\delta(\Delta v)}{\delta(\Delta P)} = \frac{c}{n\lambda} \frac{4kbC}{\pi r}$$

5   wherein n and λ are average indices of birefringence and laser wavelength. For k=1, 2r=125μ, C=3,11*10^{12} m^2 /N and λ = 1,55 μm, the sensitivity S will typically be 1-10MHZ/mbar for b=1-10 mm. The differential pressure resolution of the sensor 2ΔV_{beat}/S, with the unit mbar.

10   With a typical beat bandwidth ΔV_{beat}<100kHz, and b=10mm, the resolution will be better than 0,01 mbar. This will also be the resolution at a measurement of absolute pressure P_2 when P_1 is known.

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Claims:

1.   Method for application of an optical fibre laser
with distributed feed back via a fibre Bragg-grating in
the fibre core (DFB fibre laser), comprising an amplify-
ing optical fibre doped with one or more rare-earths, in
which the grating is arranged on at least a part of the
amplifying fibre to achieve distributed feed back, and
in which, with at least one phase-discontinuity in the
grating, the laser effect only operates on two wave-
lengths, λ_{Bx} and λ_{By}, with orthogonale polarisation modes,
or only one of said wavelengths if the other wavelength
is suppressed characterized in that the fiber laser, or
particularly the fiber core in which the light is
transferred and the grating is provided, is exposed to
an external perturbation, including pressure, stretch
and temperature, which changes the effective indices of
birefringence of the laser mode or the length of the
fibre laser and thus alters the laser wavelengths.

2.   Method according to Claim 1, characterized in that
the fiber laser core is exposed to an asymmetrical
transverse force, including a perturbation which induces
a birefringence in the fibre, and including a stretch
changing the wavelength difference between λ_{Bx} and λ_{By}.

3.   Method according to Claim 1, for measurements,
characterized in that the parameter to be measured
induces an asymmetrical, transversal force against the
fiber, causing a birefringence or stretch in the fibre
and thus a measurable change of the wavelength differ-
ence between λ_{Bx} and λ_{By}, or a shift in absolute laser
wavelength for a laser with only one wavelength, or
both wavelengths for a laser oscillating on both ortho-
gonal polarisations modes.

4.   Method according to Claim 1, in which the fibre
laser is applied as a source with two othogonally
polarized wavelengths, characterized in that a con-

trolled asymmetrical traverse force against the fire
controls the wavelength difference between λ_{By} and λ_{By}
through birefringence.

5. Fibre optical end fed fibre laser (DFB fibre laser)
5   for conducting of the method of Claims 1-4, particularly
as a sensor for measurements, characterized in that it
is arranged for measuring of the distance   between the
orthogonal Bragg wavelengths λ_{Bx} and λ_{By}, which are cre-
ated when birefringence is generated in the laser, or
10   the fibre is stretched and/or provided for measuring of
absolute laser wavelength for a laser with only one
wavelength or average wavelength, or both wavelengths
for a laser oscillating on both orthogonal polarisation
modes.

15   6. Fibre optical laser according to Claim 5, provided
for use as a sensor in measurements, characterized in
that it is provided for asymmetrical transversal pres-
sure depending on the parameter to be measured, to
induce doble refraction in the laser.

20   7. Fibre optical laser according to Claim 5 or 6,
characterized in that it is provided to measure simul-
taneously of two different parameters, e.g. pressure and
temperature, by measuring the distance $\Delta\lambda$ between the
wavelengths and the absolute value of one (or both)
25   individual Bragg wavelengths λ_{Bx} and λ_{By}.

8. Fibre optical laser according to one of the Claims
5, 6 or 7, characterized in that several sensor ele-
ments are serially multiplexed along one fibre or in
parallel in different fibres (Fig. 4a, 4b).

30   9. Fibre optical laser according to Claim 5, charac-
terized in that it is provided to be used as an optical
source with two orthogonal wavelengths, in one array.

10. Fibre optical laser according to Claim 5, charac-
terized in that it is provided for use as a reading
35   means for interferometrical sensors generally, and

polarometric sensors specially, in which said two wavelengths has an adjustable separation and may ensure quadrature operation.

11. Fibre optical laser according to Claim 5, characterized in that it is used as a source for generating a beat signal, which by non-linear propagation in a dispersion-profiled fibre is developed into a pulse train with adjustable frequency of repetition equal the frequency separation between the modes of polarization.

12. Fibre optical laser according to Claim 5, characterized in that it is provided with a device for transferring the desired external impact to a change in the double refraction of the fibre laser, and thus wavelength separation between the orthogonal modes of the laser.

13. Fibre optical laser according to Claim 5, characterized in that the wall pressure of a pipe is introduced as a radial force against the fibre, to measure the flow of the pipe.

Application No: GB 9605822.7   **Examiner:**   Martyn Dixon
Claims searched: all   **Date of search:**   7 May 1996

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

    UK Cl (Ed.O): H1C (CCA); G1A (ABF,ACFG,ADRG)

    Int Cl (Ed.6): H01S (3/06); G01L (11/02)

Other: online: WPI,INSPEC

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
A	WO 95/31020 A (University of Southampton) the whole document	1
X	US 5166940 A (Charles Stark Draper Lab) see especially fig 15 and column 5, lines 16-27	1-3,5 at least

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